Modeling Noise Equivalent Change in Radiance (NEdN) for the Cross-track Infrared Sounder (CrIS)

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ABSTRACT

It is important in any remote sensing radiometer to identify and characterize the noise and error sources of the radiometer. At ITT, we have produced a number models to characterize noise and its impacts. The latest noise model is for the Cross-track Infrared Sounder (CrIS) instrument which is part the National Polar-orbiting Operational Satellite System (NPOESS). The required accuracy of the instrument mandates identifying and characterizing the noise and error sources such that these sources can be optimized and managed to mitigate risk to instrument performance.

For radiometers the nominal way of describing noise and random errors is through the use of Noise Equivalent Change in Radiance or NEdN. NEdN is a way to project the noise from the system back to the scene such that the overall effect can be compared with the true signal (that coming from the scene).

This paper will present descriptions of these terms as well as a comparison between the theory and measurements from the first CrIS Engineering Development Unit (EDU).

Keywords: interferometer, Fourier transform spectrometer, sounder, remote sensing, CrIS, noise equivalent change in radiance.

1. BASIC NEDN EQUATION

For radiometers the nominal way of describing noise and random errors is through the use of Noise Equivalent Change in Radiance or NEdN. NEdN is a way to project the noise from the system back to the scene such that the overall effect can be compared with the true signal (that coming from the scene). The general form for NEdN is as follows:

$$NEdN = \frac{Noise}{A\Omega \cdot \tau_o \cdot \rho \cdot \Delta\upsilon}, \quad (1)$$

where $Noise$ is the characterization of the noise or error source in terms of signal noise,
$A\Omega$ is the etendue (throughput) of the instrument defined by the view of the instrument and the detector size,
τ_o is the optical attenuation of the instrument,
ρ is the detector responsivity,
and $\Delta\upsilon$ is the optical bandwidth.

2. INTERFEROMETER SPECIFIC NEDN

An important part of providing the Cross-track Infrared Sounder (CrIS) instrument for the National Polar-orbiting Operational Satellite System (NPOESS) program, is being able to characterize the sensor's performance. On major performance issue is the accuracy of the radiometry, to this end ITT has developed a tool to help identify risk from noise and error sources for the designed instrument. The implementation of equation 1 (above) is the backbone of the model. Because CrIS is an interferometric system some of the terms in the NEdN equation need to be expanded.

1. $Noise/\Delta\upsilon$ becomes $2 \cdot L \cdot Noise/\sqrt{T}$

where L is the maximum optical path difference of the interferometer ($2 \cdot L$ for a doubled sided systems),
$Noise$ is the noise spectral density at the detector in Amps/√Hz,
and T is the time required for one full double sided interferogram.

2. τ_o becomes $\tau_o \cdot \eta_{BS} / 2 \cdot \mu$

where τ_o is the optical transmission of the sensor excluding the interferometer beamsplitter,

η_{BS} is the "Beamsplitter Efficiency", losses from the beamsplitter coating,

and μ is the "Modulation Efficiency", losses from misalignment and wavefront errors.

3. $A\Omega$ becomes $A\Omega \cdot EtendueFactor$

where $EtendueFactor$ is used to account for any obscurations through the system.

With these changes the NEdN Equation for Eq. 1 becomes:

$$NEdN = \frac{4 \cdot L \cdot Noise}{A\Omega \cdot EtendueFactor \cdot \tau_o \cdot \eta_{BS} \cdot \mu \cdot \rho \cdot \sqrt{T}} . \qquad (2)$$

Once the *Noise* terms are defined the NEdN can quickly be calculated. However, to determine the *Noise* terms is no small matter. Because the *Noise* term is defined as the noise spectral density at the detector, the noise and error sources for the interferometer and electronic components must be converted to a noise at the detector before being added in quadrature, i.e. root-sum-squared (RSSed), for a total system noise.

3. NOISE AND ERROR SOURCES FOR CRIS

There are a number of ways that the measurements made by the CrIS instrument could be contaminated by noise and/or errors. These sources of these noise/errors can grouped into classes. Some are directly involved with the detection of photons, others may cause the sample to be taken at the wrong optical path difference along the interferometers scan, and others may just add/subtract from the digital number output of the sensor. There are six major groups of noise/errors, they include:

1. Detection – noise in the detecting the photons (includes detector preamplifier effects),
2. Quantization – noise from the analog signal to digital number transformation,
3. Sampling – errors from both location (OPD) errors and timing errors,
4. Alignment – errors from moving mirror jitter,
5. Aliasing – error from contamination of out-of-band signal getting in-band,

   and
6. Electronics and EMI – noise from other electronics and Electro-Magnetic Interference.

Here is a figure that shows the relationship between error and noise sources.

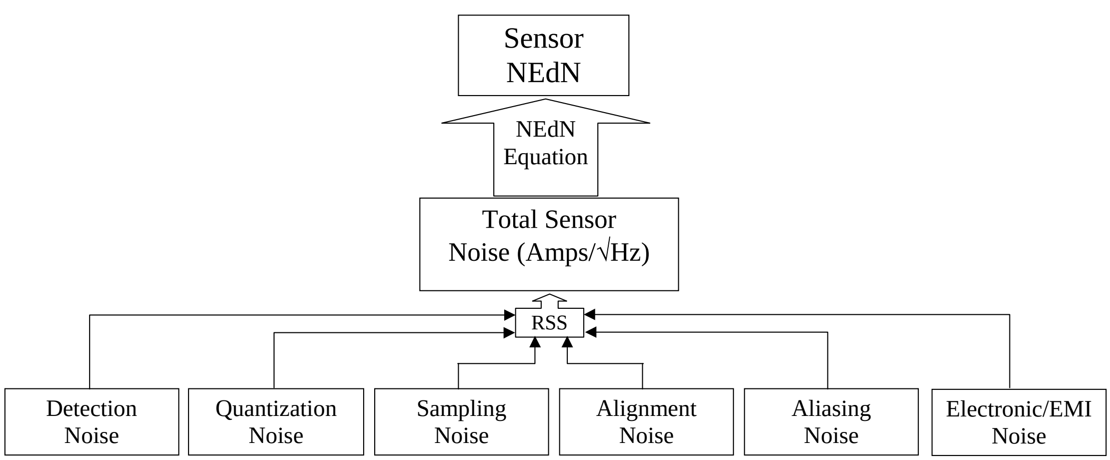

Figure 1: Noise Component Relationship to Sensor NEdN

Many of these groups can be broken down further to help flow down requirements to hardware. The following sections will discuss each noise/error source in more detail.

3.1. Detection Noise

The Detection Noise is the noise contaminating the signal during signal detection. The Detection Noise is the dominant noise source of noise for the CrIS instrument. This noise involves all noises from the detector and the preamplifier. It is this noise that is used to calculate the D* (detectivity merit function) of the detector (see equation 3).

$$D^* = \frac{\rho \cdot \sqrt{A_{Detector}}}{N_{Detector}}, \tag{3}$$

where ρ is the detector responsivity
$A_{Detector}$ is the area of the detector,
and $N_{Detector}$ is the Detection Noise.

The detection noise includes effects from:

1. Detector Shot Noise
   a. Photocurrent shot noise – noise in detection caused by the signal and background photon loads
   b. Dark current shot noise – noise in detection intrinsic to the detector operating state
2. Detector Johnson Noise – noise in detection from the detectors operating resistance circuit
3. Detector 1/f Noise – noise in detection from 1/f phenomena
4. Detector Preamplifier Noise – noise in detection from the preamplifier

These noise values are added in quadrature, RSSed, to determine the total detection noise. Of these noises sources the photocurrent shot noise is the most difficult to calculate. The photocurrent shot noise is related to the total photon load on the detector, not just the signal photons, but the background photons as well. Knowing what the photon load at the detector is requires extensive knowledge of the optical design and optical material properties. In fact a large portion of the model is actually dedicated to determining the photon load on the detector.

3.1.1. Photocurrent Shot Noise / Photon Load on the Detector

The Photocurrent Shot Noise contributes a large percentage of the Detection Noise. Because of this it is very important to understand the sources of photons and how to potentially limit them. The Photocurrent Shot Noise is dependent on the square root of the photon load on the detector, both from the scene and from the emission of the warm optics in the sensor.

The photon load on the detector is dependent on the properties optical components in front of it, and its view of those components. For the model it is assumed that each component emits photons similarly to a graybody emitter at the component's temperature with an emissivity equal to 1-(R+T), where R is the components reflectance and T is its transmissivity. The detector views each component with a certain viewing factor (related to etendue of the component as viewed from the detector) potentially through some other components. The photons reaching the detector from the ith component in front of the detector may be calculated using:

$$photons_i = \varepsilon_i \cdot Planck(T_i) \cdot ViewFactor_i \cdot \prod_{j=1}^{i-1} \tau_j \ , \tag{4}$$

where ε_i is the emissivity of the ith component,
$Planck(T)$ is a function for the photons/sr/cm² emitted from a blackbody emitter at temperature T,
T_i is the temperature of the ith component,
$ViewFactor_i$ is the viewing factor of the ith component (units are cm²·sr),
and $\prod_{j=1}^{i-1} \tau_j$ is the product of transmissions of all components between the detector and the ith component.

The following figure illustrates a potential optical layout.

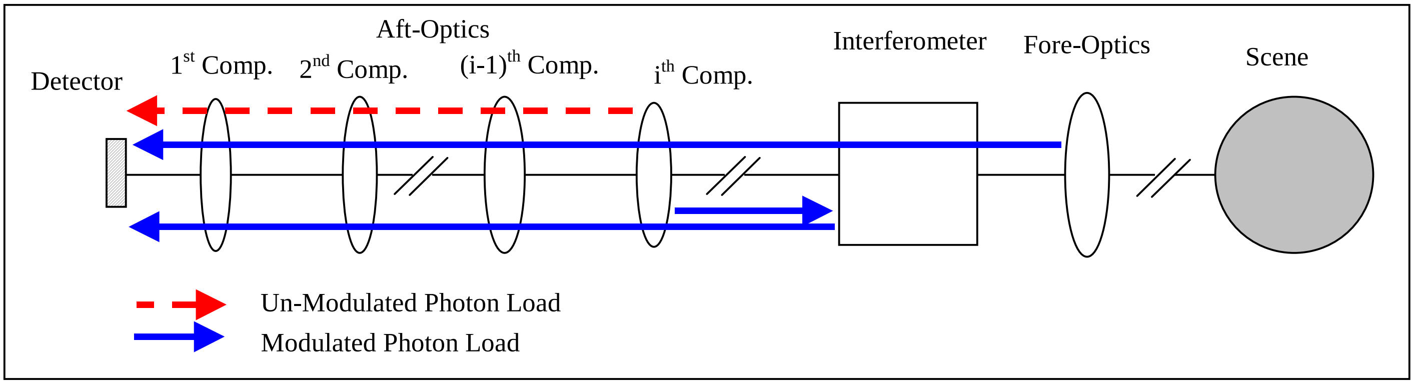

Figure 2: Potential Optical Layout Used for Photon Load Calculations

Because the CrIS instrument is an interferometer system, the photon load from fore-optics in front of the interferometer module (i.e toward the scene) will be modulated similarly to the scene photon load. Another interesting and important point is that photons being emitted from the components go in all directions, so aft-optics components (i.e. towards the detector from the interferometer) will emit photons that go toward the interferometer. At the interferometer the photons will be either sent out of the sensor toward the scene, or reflected back towards detector. The average photons that get reflected back to the detector should also be included in the photon load at the detector when calculating the photocurrent shot noise. The calculation of these photons is similar to that in equation 4 with the addition of double the transmissions from the component to the interferometer and the transmission of the component itself.

The total photon load on the detector becomes:

$$photons = \sum_{1}^{i_{scene}} \left(\varepsilon_i \cdot Planck(T_i) \cdot ViewFactor_i \cdot \prod_{j=1}^{i-1} \tau_j \right) + \left(\sum_{i=1}^{i_{intpos}} \varepsilon_i \cdot Planck(T_i) \cdot ViewFactor_i \cdot \prod_{j=i+1}^{intpos-1} \tau_j \cdot \prod_{k=1}^{intpos} \tau_k \right) \qquad (5)$$

where *intpos* is the position of the interferometer and the transmission of the interferometer, τ_{intpos} is ~ $\frac{1}{2} \cdot \eta_{BS}$.

3.1.2. Detector Intrinsic Noises

The detector has electronic noise just from being a detector, these noises are intrinsic to the operating state of the detector and independent of the photon load on the detector. The dark current of the photo diode adds some Shot Noise into the total noise of the detector. The Dark Current Shot Noise is about half as large as the Photocurrent Shot Noise in magnitude.

The Johnson Noise of the detector coupled with a resistor also adds noise to the detection. The Johnson Noise is about a factor of five (5) less in magnitude than the Photocurrent Shot Noise, thus when added in quadrature becomes rather insignificant.

Finally, there is also 1/f phenomena, noise that goes inversely as the frequency of the measurements, associated with the detector. This 1/f noise is in the band of the instrument, at least for the longwave band. This 1/f noise is of the same magnitude as the Photocurrent Shot Noise, thus any reduction in the 1/f noise will increase sensor performance.

3.1.3. Detector Preamplifier Noises

As stated previously the Detection Noise includes effects from the detector preamplifier. The magnitude of this noise is approximately half of that of the Photocurrent Shot Noise.

3.2. Quantization Noise

In the conversion from an analog signal to a digital number output an uncertainty from this process is added to the output signal. This uncertainty manifests itself as a noise.

3.2.1. Analog to Digital Converter Quantization

The analog to digital converter A/D converter takes an analog signal and converts it to a digital number. This process involves "binning" the analog signal. Since any one analog signal must fall into on digital number, but one digital number may be created by a number of analog signals, there is an uncertainty in the digitized number. This uncertainty is considered to be a noise source.

3.2.2. FIR Filter Quantization

The FIR filter is used to decimate the captured interferogram. The decimation effectively reduces the number of samples by a factor of 24 for the longwave. The process of decimation added more uncertainty to the output digital number and that uncertainty can be treated as a noise source.

3.3. Sampling Errors

Sampling of the signal is extremely important when working with an interferometer. Errors in sampling are result in a measurement of the signal at the wrong optical path difference (OPD). These errors may be cause by a lack of knowledge of the true path difference, or by an incorrect sample timing, but the result is still of a sample taken at the wrong OPD. Sampling errors will add to spectral uncertainty when the interferogram is Fourier transformed into a spectra. The effect can again be thought of as an NEdN noise source. There are four major causes of sampling errors:

1. Porch Swing Velocity Error – an OPD error,
2. Metrology Laser Wavelength Drift – an OPD error,
3. Electronic Circuit Delay Mismatch Drift – a sample timing error
4. Quantization Delay – a sampling timing error

3.3.1. Porch Swing Velocity Jitter

The Porch Swing , or moving mirror, of the interferometer ideally moves at a constant velocity while measurements for the interferogram are being taken. However, because the moving mirror is actually a driven system with a servo feedback loop, the velocity of the porch swing may very from individual measurement to measurement. This changing velocity will become result in samples being measured at the wrong OPD.

3.3.2. Metrology Laser Wavelength Drift

The metrology laser is used to monitor the OPD as samples are taken. This is done by determining the zero-crossings (2 per metrology wavelength) of the interference of the metrology laser as it goes through the interferometer. If the wavelength of the metrology laser changes the physical path difference between zero-crossings will change, and there for the OPD will change between samples for the measured interferogram. For the CrIS instrument a highly stable laser is used to minimize OPD errors caused by metrology wavelength drifts.

3.3.3. Electronic Circuit Delay Mismatch Drift

Because the signal from the metrology and the signal to measured (the IR signal) are collected on different electrical circuitry there is some electronic mismatch between the two. The two signals are delay matched so that they both are recorded at about the same time. There is some uncertainty in the delays and therefore the signals are recorded at slightly different times resulting in an OPD error

3.3.4. Quantization Delay

There is also a delay during quantization that causes the sampling to be off in OPD spacing.

3.4. Interferometer Alignment Jitter

While the Porch Swing is moving along the OPD path (the optical axis), it will also be rotating and tilting. While rotations and tilts may be small, on the order of µradians, they impact the modulation efficiency of the interferometer. Essentially a fringe of a monochromatic source would move across the detector reducing the contrast of the measure signal. The result when looking at a broad spectrum is a change in the spectral modulation efficiency. This means that every point in the interferogram may have a slightly different spectral modulation efficiency. This changing modulation efficiency can be treated as a noise source.

3.5. Aliasing Contamination

Because the CrIS instrument is a Fourier Transform Spectrometer (FTS) system it measures spatial frequencies of spectral data. When the data is converted to a spectra from spatial samples using a Fourier transform, some higher order spatial frequencies may be aliased into the band of interest. There are a number of components that can add aliased signal back in-band.

3.5.1. Analog to Digital Converter Aliasing

The A/D converter can alias the signal, but it also has an anti aliasing filter to minimize this effect

3.5.2. FIR Filter Aliasing

The FIR Filter can alias as well.

3.5.3. Other Source Aliasing

Th low-pass filter can also allow some aliasing, and well

3.6. Electronics Noise and EMI

The electronic of the system, other than the detector and preamplifier, can also add electronic noise to the system. Also the electric fields and magnetic fields can also add noise.

4. ENGINEERING DEVELOPMENT UNIT (EDU)

To mitigate many of the design risks to the CrIS program ITT built an Engineering Development Unit, or EDU. This unit was used to validate a lot of the design, and helped determine other potential risks. One test that was run on the EDU was to measure its NEdN. These measurements could then be compared with the predicted results from the model.

4.1. EDU NEdN Measurements

A number of measurements were taken to determine the NEdN of the EDU. The EDU had only the longwave band and the bands extent was greatly reduced compared to the flight design, $650cm^{-1}$ - $900cm^{-1}$ rather than $650cm^{-1}$ - $1095cm^{-1}$. The following plot shows the measured NEdN of the EDU (see Figure 3).

EDU Measured NEdN

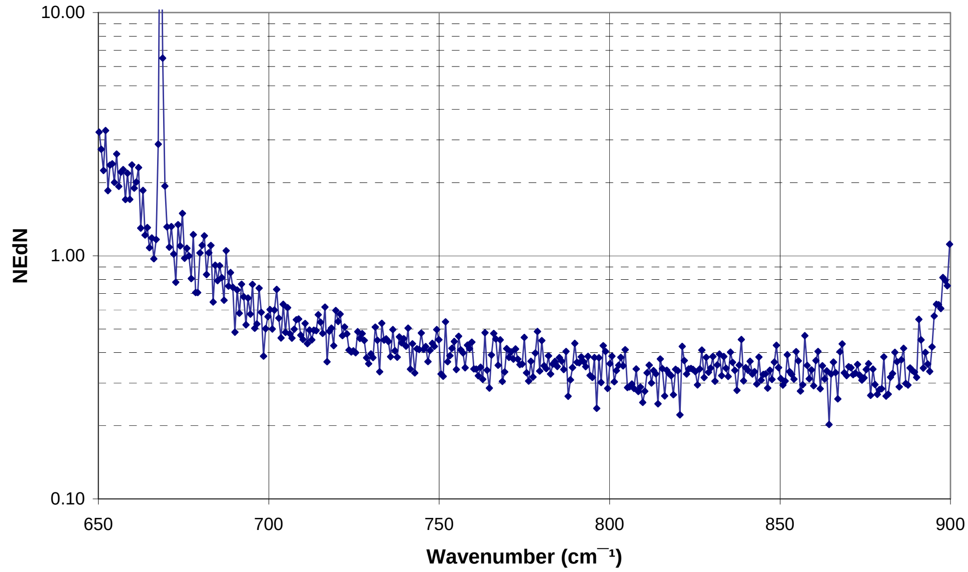

Figure 3: NEdN measured for the CrIS EDU

4.2. Model Predictions for EDU

The model was updated to reflect the parameters of the EDU unit and the resulting predictions are shown in Figure 4.

EDU NEdN, Measured and Modeled

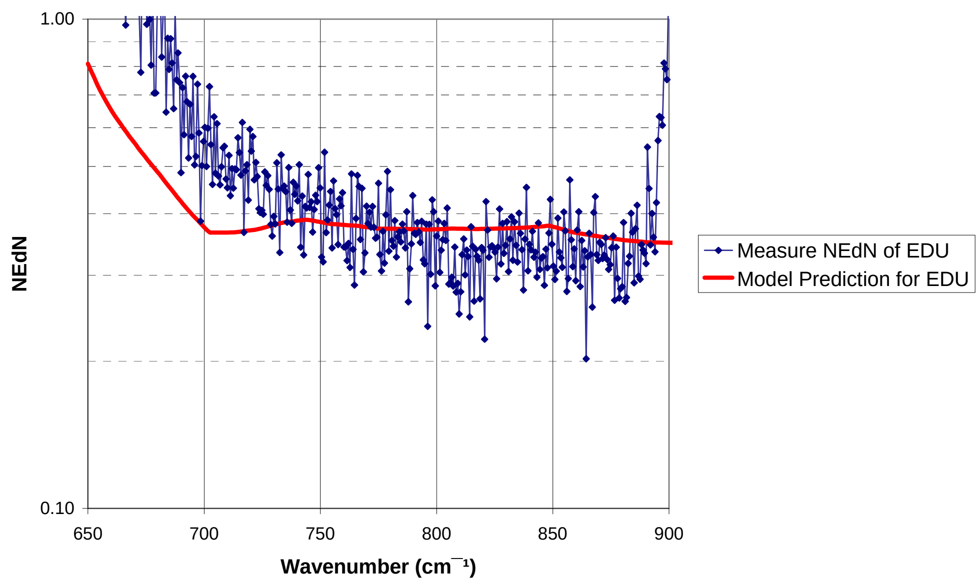

Figure 4: Modeled NEdN Prediction compared with measured NEdN for the CrIS EDU

The NEdN shape is heavily influenced by the detector responsivity and optical bandpass filters. Both of these components begin decreasing in performance

As can be seen from the plot, for most of the band there is very good agreement. The longwave edge may be contaminated by atmospheric effects or lack of knowledge of the components used to make the EDU. With this agreement ITT feels confident in its ability to model the NEdN Performance of the CrIS flight design.

5. ACKNOWLEDGEMENTS

6. REFERENCES